NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT 1240

AN INVESTIGATION OF THE EFFECTS OF HEAT TRANSFER ON BOUNDARY-LAYER TRANSITION ON A PARABOLIC BODY OF REVOLUTION (NACA RM-10) AT A MACH NUMBER OF 1.61

By K. R. CZARNECKI and ARCHIBALD R. SINCLAIR

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National Advisory Committee for Aeronautics

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AN INVESTIGATION OF THE EFFECTS OF HEAT TRANSFER ON BOUNDARY-LAYER TRANSITION ON A PARABOLIC BODY OF REVOLUTION (NACA RM-10) AT A MACH NUMBER OF 1.61†

By K. R. Czarnecki and Archibald R. Sinclair

SUMMARY

An investigation has been made of the effects of heat transfer on boundary-layer transition on a parabolic body of revolution (NACA RM-10 without fins) at a Mach number of 1.61 and over a Reynolds number range from 2.5×10^6 to 35×10^6. The maximum cooling of the model used in these tests corresponded to a temperature ratio (ratio of model-surface temperature to free-stream temperature) of 1.12, a value somewhat higher than the theoretical value required for infinite boundary-layer stability at this Mach number. The maximum heating corresponded to a temperature ratio of about 1.85. Included in the investigation was a study of the effects of surface irregularities and disturbances generated in the airstream on the ability of heat transfer to influence boundary-layer transition.

The results indicated that cooling the model increased the Reynolds number for which laminar flow could be maintained over the entire length of the body, whereas heating the model decreased this transition Reynolds number. The trend of the experimental results is in good agreement with that predicted by boundary-layer stability calculations. The highest transition Reynolds number obtained with cooling was 28.5×10^6. At this Reynolds number the classical Tollmien-Schlichting wave type of boundary-layer instability was apparently overshadowed by surface roughness effects. Heating the model so that the ratio of model-surface temperature to free-stream temperature was 1.85 decreased the transition Reynolds number to about 3×10^6. The effects of heat transfer on transition were considerably larger than previously found in similar investigations. It appears that, if the boundary-layer transition Reynolds number for zero heat transfer is large, then the sensitivity of transition to heating or cooling is high; if the zero-heat-transfer transition Reynolds number is low, then transition is relatively insensitive to heat-transfer effects. The results also indicated that, when transition was fixed by surface irregularities or airstream disturbances, cooling was not effective in obtaining laminar flow behind the irregularity or disturbance.

INTRODUCTION

In the design of supersonic airplanes and missiles, much dependence is placed upon experimental values of skin-friction drag. Wind-tunnel investigations of skin friction, however, are usually made under conditions of little or no heat transfer. In actual flight of high-speed aircraft, particularly during acceleration or deceleration, the temperature of the vehicle often lags behind that of the boundary layer. Under these conditions, the heat transfer to or from the boundary layer may be appreciable.

Theoretical considerations (refs. 1 to 3) have indicated that one of the most important effects of heat transfer is its influence on the stability of the laminar boundary layer. In particular, it appears to be theoretically possible to preserve the laminar boundary layer at high Reynolds numbers by means of heat transfer from the boundary layer into the body. Unfortunately, in its present state of development, the theory is unable to predict the magnitude of this effect with certainty, particularly at the higher supersonic speeds.

Previous wind-tunnel experiments (refs. 4 to 8) have established the existence of the expected effects of heat transfer, but the magnitude of the stabilizing effect of heat transfer from the boundary layer to the body was not large. It should be noted, however, that in the previous tests the transition Reynolds numbers for zero heat transfer were relatively low, of the order of 1.3×10^6.

The zero-heat-transfer transition Reynolds number for a slender parabolic body obtained in a preliminary investigation in the Langley 4- by 4-foot supersonic pressure tunnel was found to be about 11×10^6, a value considerably greater than that found in the investigations of references 4 to 8. This result suggested the possibility of investigating the effects of heat transfer on boundary-layer stability for an experimental setup having a large initial transition Reynolds number. A test model which could be either heated or cooled internally was accordingly constructed and tests were made at zero angle of attack at a Mach number of 1.61 for a range of Reynolds number from 2.5×10^6 to 35×10^6. The results of the investigation are presented in this report.

During the preparation of this report, a flight investigation in which large heat-transfer effects on boundary-layer stability were observed was reported in summary form (ref. 9). The details of this investigation have since been published in reference 10.

SYMBOLS

C_{D_F}	skin-friction-drag coefficient, $\frac{\text{Skin-friction drag}}{qA}$
A	maximum cross-sectional area of body
M	free-stream Mach number

† Supersedes NACA TN's 3165 and 3166 by K. R. Czarnecki and Archibald R. Sinclair, 1954.

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q	free-stream dynamic pressure
L	length of model
x	distance along model from nose
r	radius of body
R	Reynolds number based on body length and free-stream conditions
R_{tr}	transition Reynolds number
T_e	model equilibrium temperature without heating or cooling, °F
T_w	model surface temperature with heating or cooling, °F
T_0	stagnation temperature, °F
ΔT	average temperature difference for model, $T_w - T_e$, °F
$\frac{\Delta T}{T_0'}$	average temperature-difference ratio for model
T_∞	free-stream temperature, °F
T_w'/T_∞'	average ratio of model surface temperature to free-stream temperature
u	stream-direction component of velocity fluctuations
U_∞	free-stream velocity
$\frac{u'}{U_\infty}$	root-mean-square of u-velocity fluctuation level, $\sqrt{\frac{\overline{u^2}}{U_\infty^2}}$

A prime mark over a temperature symbol (for example, T_0') indicates absolute temperature.

APPARATUS AND TESTS

WIND TUNNEL

The investigation was conducted in the Langley 4- by 4-foot supersonic pressure tunnel which is a rectangular, closed-throat, single-return wind tunnel with provisions for the control of the pressure, temperature, and humidity of the enclosed air. Changes in test-section Mach number are obtained by deflecting the top and bottom walls of the supersonic nozzle against fixed interchangeable templates which have been designed to produce uniform flow in the test section. The tunnel operates over a range of stagnation pressure from about ⅛ to 2¼ atmospheres and over a nominal Mach number range from 1.2 to 2.2. For qualitative visual-flow observation, a schlieren optical system is provided.

For the tests reported herein, the nozzle walls were set for a Mach number of 1.61. At this Mach number, the test section has a width of 4.5 feet and a height of 4.4 feet. Calibrations of the flow in the test section indicate that the Mach number variation about the mean value of 1.61 is about ±0.01 in the region occupied by the model and that no significant irregularities occur in the stream flow direction. The turbulence level measured on the center line of the tunnel in the entrance cone is shown in figure 1.

MODEL

A sketch of the NACA RM–10 model without fins, giving pertinent dimensions and construction details, is shown in figure 2 and a photograph of the model is presented as figure 3. The body has a parabolic-arc profile with a basic

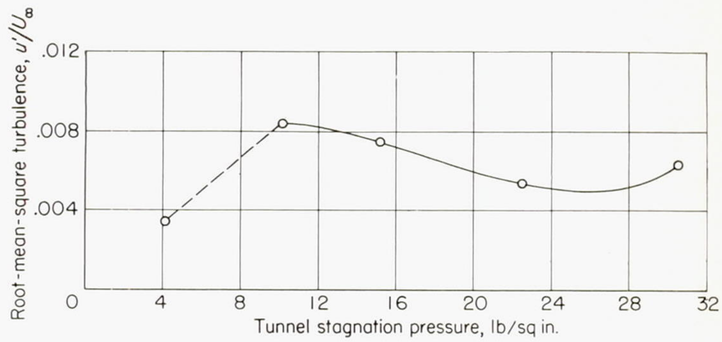


FIGURE 1.—Turbulence level on center line of tunnel in entrance cone. Average velocity U_∞ at point of measurement, 155 feet per second.

fineness ratio of 15. The equation for the basic body of revolution is:

$$r = 0.1333x - 0.00217x^2$$

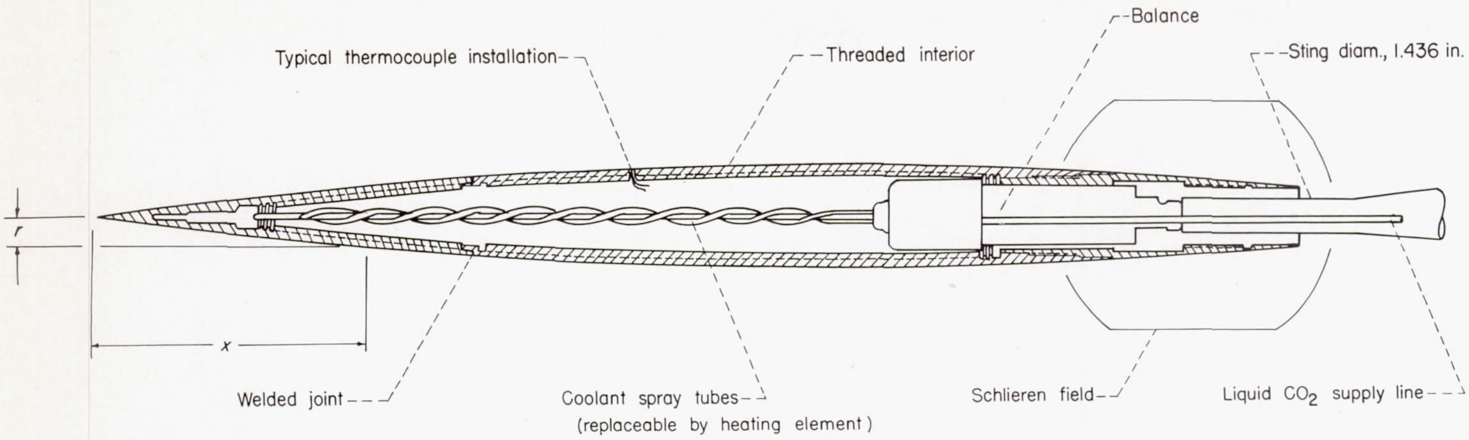
The pointed stern of the basic body was cut off at 81.25 percent of the basic length, however, so that the actual body has a blunt base and a fineness ratio of 12.2. The model of the present tests has a length of 50 inches and a maximum diameter of 4.096 inches.

The model was constructed of aluminum alloy in two sections, which were hollowed out. The joint between the sections, which occurred at the 84.5-percent body station, was carefully sealed and faired until no discontinuity at the surface could be detected. Body contours were not measured but are estimated to be accurate to within an average deviation from the design contour of 0.006 inch and a maximum possible deviation of about 0.020 inch. Surface roughness (determined by means of a Physicists Research Co. Profilometer, Model No. 11) varied between 4.5 and 6 microinches root mean square over most of the model and increased to about 12 microinches root mean square in a very small region close to the base of the body.

TEST PROCEDURE

The investigation was made in two phases. In phase I the Reynolds number range was from 7×10^6 to 20×10^6 and boundary-layer transition was determined from boundary-layer surveys and schlieren observations. The heating and cooling range was from about 18° F above model equilibrium temperature to 90° F below this reference temperature. In phase II the Reynolds number was increased to a range extending from 2.5×10^6 to 35×10^6, the heating range was increased to about 170° F above equilibrium temperature, and a more extensive study was made of the effects of surface irregularities and airstream disturbances on the ability of heat transfer to influence boundary-layer transition. In addition, the experimental techniques were expanded to include force tests.

During phase I, heating or cooling mediums (steam for heating and liquid carbon dioxide for cooling) were introduced into the hollowed-out model by means of three tubes, one of which was ¼ inch in outside diameter and the other two, wrapped around the larger, were ⅛ inch in outside diameter. Small holes were drilled along the lengths of



Termocouple locations		
Station, in.	Number	Spacing, deg
3.0	2	180
12.6	2	180
22.4	4	90
32.0	2	180
37.1	2	180
46.0	2	180

FIGURE 2.—Sketch of NACA RM-10 model and apparatus for heating and cooling. Model length, 50.0 inches; maximum diameter, 4.096 inches.

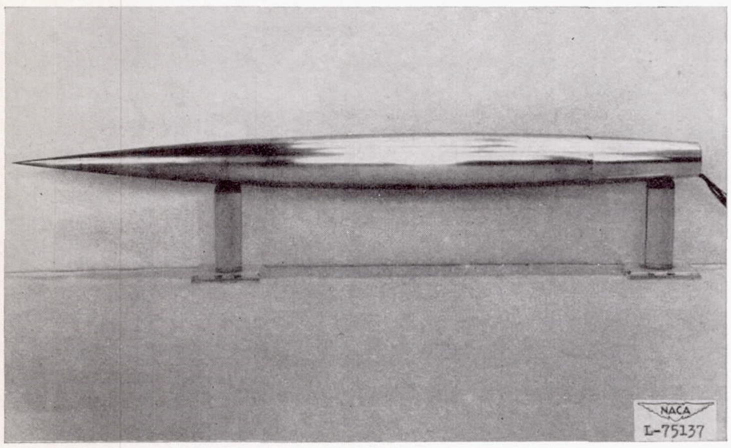


FIGURE 3.—NACA RM-10 model.

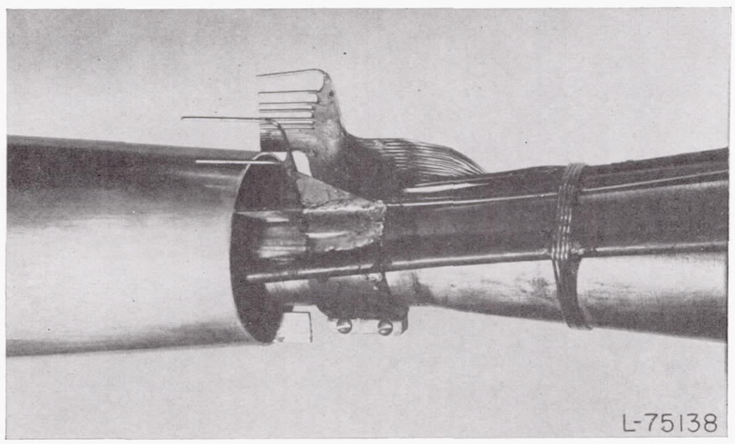


FIGURE 4.—Model base showing details of boundary-layer survey rake.

these tubes to act as spray orifices. The inside of the model was deeply grooved, wherever possible, to increase the exposed surface area and to induce turbulence in the heating or cooling gas flow so that a high rate of heat transfer would be favored. Supply lines for the spray tubes were brought through the base of the model on the outside of the sting.

For phase II of the investigation, the cooling system remained unchanged, but the steam heating system was replaced by an electrical heating element consisting of a steel rod wound with heavy resistance wire, capable of operation to 1600 watts. Power input to the heating element was controlled by means of a Variac.

The model was mounted on a sting in the tunnel and an electrical strain-gage balance was mounted in the rear part of the model. This balance was operative only during phase II of the investigation. Fourteen iron-constantan thermocouples were installed in the surface of the model as shown in figure 2, and the leads were brought out through the base of the model on the outside of the sting.

Boundary-layer profiles were determined by means of a rake of tubes shown in figure 4. The rake was constructed of fifteen total-pressure tubes and two static-pressure tubes with a 0.040-inch outside diameter (0.030-inch inside diameter) chosen to meet response-time requirements, and the ten total-pressure tubes closest to the surface were flattened to a height of about 0.025 inch per tube to give closer spacing. The rake was clamped on the sting so that boundary-layer profiles were determined about $\frac{1}{64}$ inch ahead of the base of the model. Sheet-metal spacers were wedged between the

sting and the base of the model to prevent any motion of the model relative to the rake. During the investigation of the boundary-layer profiles, no force data were taken.

For the force tests with the electrical strain-gage balance, base pressures were determined by means of four total-pressure tubes of 0.060-inch outside diameter (0.040-inch inside diameter) mounted on the surface of the sting in the plane of the model base at 90° intervals. The model skin-friction drag was then obtained by subtracting the base drag and a value of forebody pressure drag from the total drag determined by the balance. Values of forebody drag coefficient assumed for the model were 0.041 when the boundary layer was essentially laminar and 0.044 when the boundary layer was turbulent. These values were estimated from pressure measurements made on another model of identical shape.

In order to eliminate any residual effects of heating and cooling when determining boundary-layer characteristics under equilibrium or adiabatic condition, in phase II all such tests were made as independent runs without heating or cooling, and ample time was allowed for the model surface temperatures to reach an equilibrium state. No such precautions were exercised during phase I of the program.

Boundary-layer transition was determined from the force tests by plotting skin-friction drag coefficient against temperature as illustrated in figure 5. Transition was assumed to occur at the intersection of the two basically different segments of the curve. The nearly horizontal part of the curve corresponds to a completely laminar boundary layer on the body, whereas the sharply sloped part of the curve at the higher temperatures corresponds to the case where transition has occurred at the base of the body and is moving forward. The transition results thus obtained checked very well with schlieren observations. For the cooling tests, data were analysed during only the warm-up cycle; for the heating tests, data were analyzed during both the heating and cool-down cycles.

During the investigation, model equilibrium or effective temperature T_e was first recorded by means of a 12-channel printing potentiometer. Boundary-layer conditions at the model base were checked by observation of the rake pressure

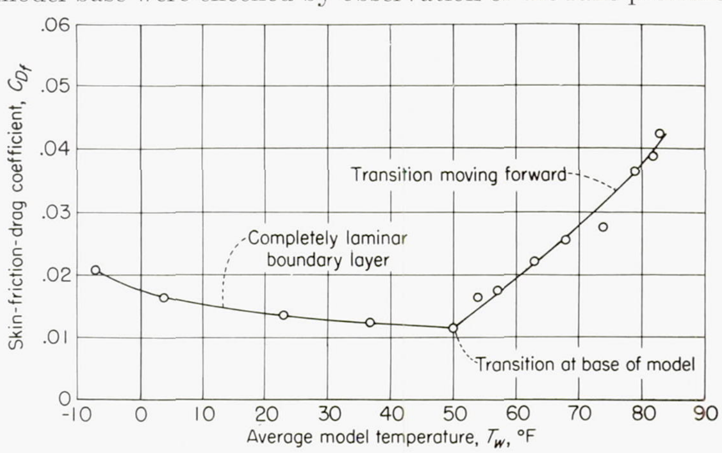


FIGURE 5.—Typical variation of skin-friction-drag coefficient with model surface temperature at constant Reynolds number. Force tests; $R=19\times10^6$; $M=1.61$.

distribution on a multitube manometer and the schlieren image. These observations made it possible to determine when transition occurred at the base of the model, the Reynolds number being varied by changes in tunnel pressure. Liquid carbon dioxide was then valved into one or more of the spray tubes as required if the model was to be cooled; steam or electrical heating was used if the model was to be heated. In general, the rate of cooling by use of carbon dioxide was much too rapid to obtain any useful data during the cooling period. Throttling of the liquid carbon dioxide to reduce the cooling rate was impractical because the lower pressure in the supply lines would result in the formation of a mixture of solid and gaseous carbon dioxide within the lines and clogging of the spray tubes by the solid dry ice.

All the cooled model data were taken during warmup, which occurred very slowly. On the other hand, during the heated model tests, the rate of heating was very slow and data were obtained during both warmup and cooling. The rake pressure distribution and the schlieren image were observed as the model temperature changed; photographs of each were made when any significant change in the boundary-layer flow was detected. Photographs were correlated with the temperature by noting each photograph on the chart of the temperature recorder which was kept running continuously. Strain-gage-balance readings were similarly correlated with schlieren observations and temperature charts.

During phase I of the investigation, tests were made with the model in the smooth condition and with circumferential roughness strips at the 4-percent, 25-percent, and 50-percent body stations. The roughness strip consisted of a ¼-inch band of shellac alone and a similar shellac band on which carborundum grains were cemented. Grain sizes used were No. 60, No. 150, and No. 250, and the grains were fairly evenly dispersed, about 150 grains per square inch.

During phase II of the investigation, tests were made with the model in a smooth surface condition and with circumferential strips of cellophane tape, 0.003-inch thick, at the 3-percent, 25-percent, and 50-percent body-length stations. Care was used to assure that the tape adhered smoothly to the model surface. A series of tests was made with a wedge of 18-inch span mounted on the tunnel floor (see fig. 6) so that the shock from the wedge impinged upon the model, usually somewhere on the forward half (x/L from 0.25 to 0.50). This wedge was cut down progressively in angle from about 10° to about 0.7° and in some cases in chord from 8 inches to 2 inches. A few tests were also made with a set of small wing or canard surfaces attached to the model at the 20-percent station (fig. 6).

All tests made of configurations other than the basic smooth model were limited to tests with cooling only. The tests were made with the model at zero angle of attack. The tunnel stagnation pressure was varied from about 2 to 30 pounds per square inch absolute, which gave a Reynolds number range, based on the model length of 50 inches, of about 2.5×10^6 to 35×10^6. Tunnel stagnation dew point was usually kept below about −30° F except at the highest test Reynolds numbers when the tunnel air was dried as much as possible (dew point about −45° F).

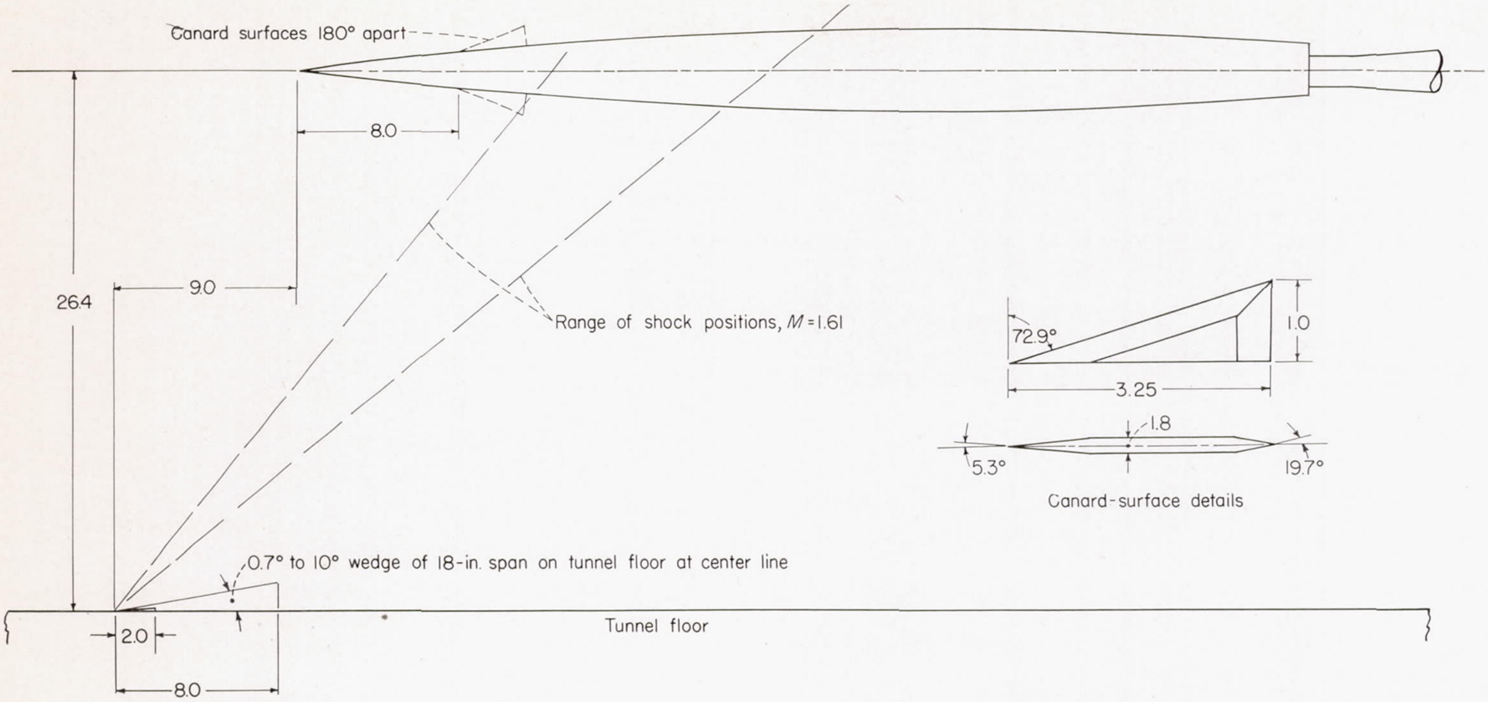


FIGURE 6.—Diagrammatic sketch showing canard location on model, and wedge setup used in investigating effects of tunnel flow disturbances. (All dimensions in inches).

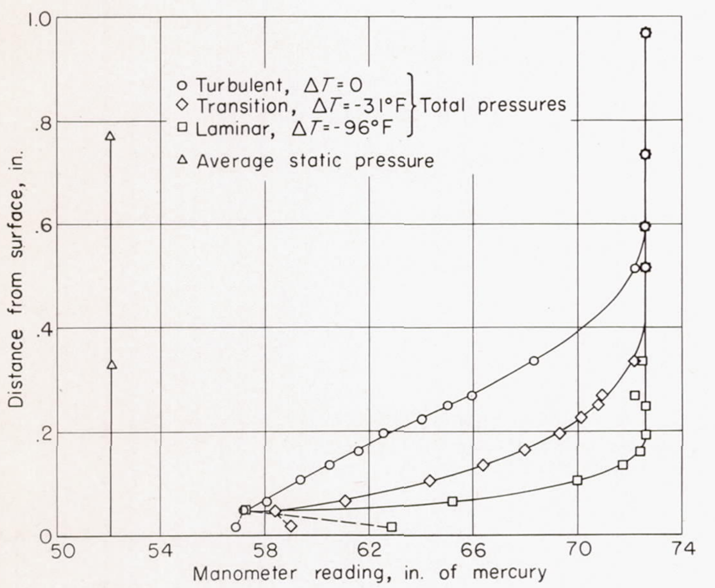


FIGURE 7.—Typical boundary-layer pressure profiles for different model temperature differentials. Phase I tests; $R=17.4\times10^6$; $M=1.61$; $T_0=109°$ F.

RESULTS AND DISCUSSION OF PHASE I TESTS

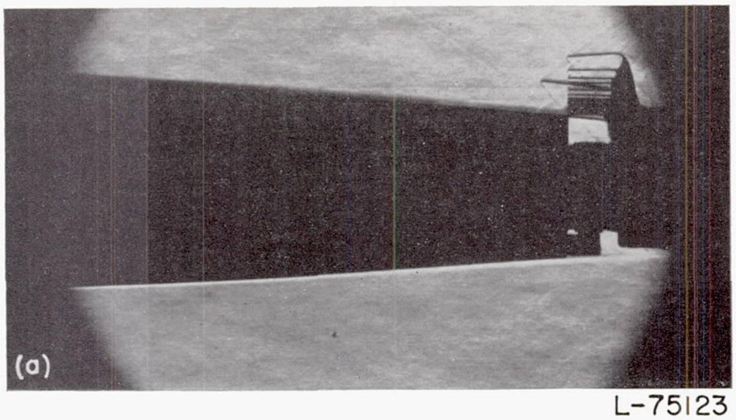
GENERAL CONSIDERATIONS

Some typical boundary-layer pressure profiles determined in the phase I tests as obtained from the manometer readings for various degrees of cooling are shown in figure 7. The pressure profiles were identified visually during tests, photographed periodically, and correlated with the continuous model-temperature records. The boundary-layer pressure profiles were identified as laminar, transition, or turbulent on the basis of: (1) the thickness of the boundary layer, (2) the shape of the pressure profiles, (3) the rate of change of boundary-layer thickness with model temperature during heating or cooling, and (4) the correlation of the thickness of the boundary layer and shape of the pressure profiles with schlieren observations. Typical schlieren photographs illustrative of laminar, transition, and turbulent flow conditions are shown in figure 8. In general, the correlation between the schlieren photographs and boundary-layer pressure surveys was excellent.

Some temperature distributions determined over the model for both heating and cooling conditions are presented in figure 9. These temperature distributions are typical of the ones measured throughout the tests. The data indicate that, immediately after heating or cooling, the temperature distribution was not uniform because of the difficulty in heating or cooling the model in the vicinity of the balance. It was not readily feasible, however, to introduce additional heating or additional coolant within the balance area. Nevertheless, as the model cooled from heating or warmed from cooling, the temperature distribution became more uniform until at the point where transition change usually first began, the variation in temperature distribution was considerably less extreme.

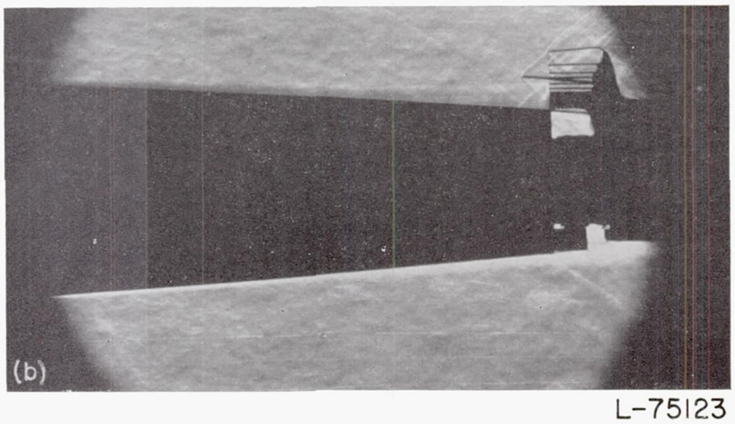
TRANSITION ON SMOOTH MODEL

A plot summarizing the effects of heating and cooling on boundary-layer transition on the RM–10 with a smooth surface from the phase I tests is presented in figure 10. Without heating or cooling, the boundary layer was laminar over the entire length of the body up to a Reynolds number of about 11.5×10^6. As the Reynolds number was increased above this value, the model had to be cooled in order to maintain laminar flow over the entire body. The amount of cooling required increased with Reynolds number until at $R=20.3\times10^6$ a temperature differential of nearly $-50°$ F was required to maintain a laminar boundary layer. Below $R=11.5\times10^6$ it was necessary to heat the model in order to induce



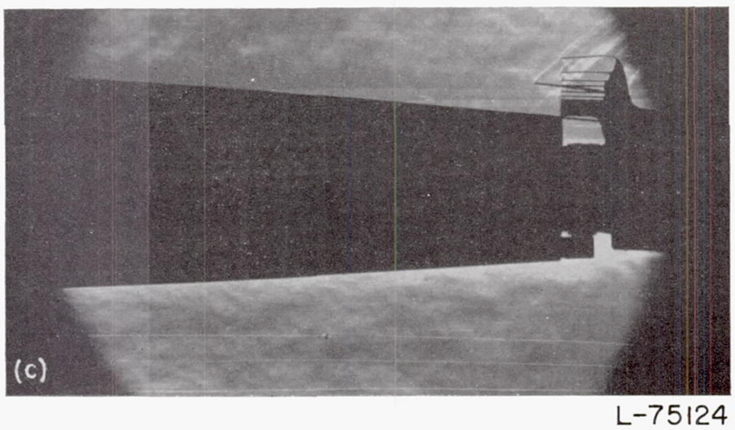
(a) Laminar; $\Delta T > -45°$ F.

FIGURE 8.—Schlieren photographs showing the various types of boundary-layer flow at base of NACA RM-10 at $R=18.3\times10^6$ with and without cooling. $M=1.61$; $T_0=109°$ F; knife edge horizontal.



(b) Transition; $\Delta T\approx -35°$ F.

FIGURE 8.—Continued.



(c) Turbulent; $\Delta T=0°$ F.

FIGURE 8.—Concluded.

turbulent flow. A temperature difference of 12° F was sufficient to cause transition at a Reynolds number of 8.1×10^6.

An examination of figure 10 also shows an apparent discontinuity in the boundary-layer transition regions for heating and cooling in the neighborhood of the Reynolds number (12×10^6 to 13×10^6) for normal transition without heat transfer. The discontinuity is probably due partly to small errors (±2° F) in the effective or equilibrium surface temperature (without heat transfer) and partly to different effective surface temperatures when the boundary layer is laminar or turbulent. The temperature recovery factors for the effective surface temperature used in the preparation of figure 10 are shown in figure 11. By making allowances for the above discrepancies in effective surface temperatures, the discontinuity in transition regions is greatly reduced if not entirely eliminated, but no reduction in the scatter of test points is obtained.

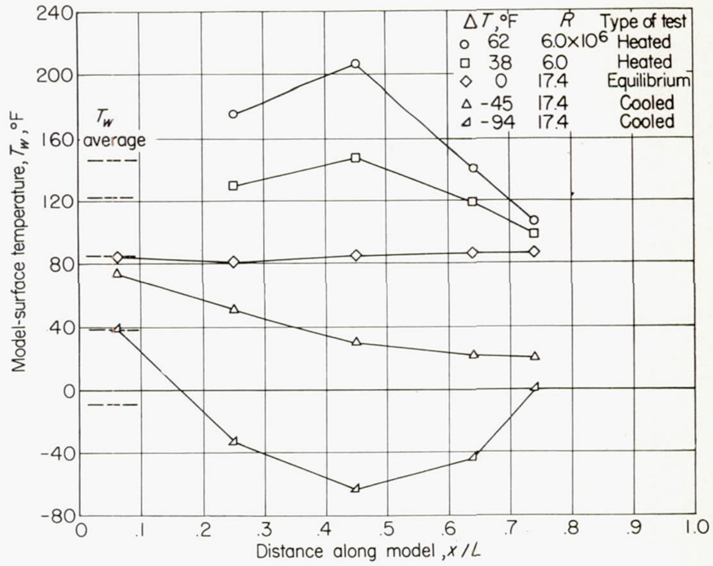


FIGURE 9.—Typical temperature distributions on model surface. $M=1.61$; $T_0=110°$ F.

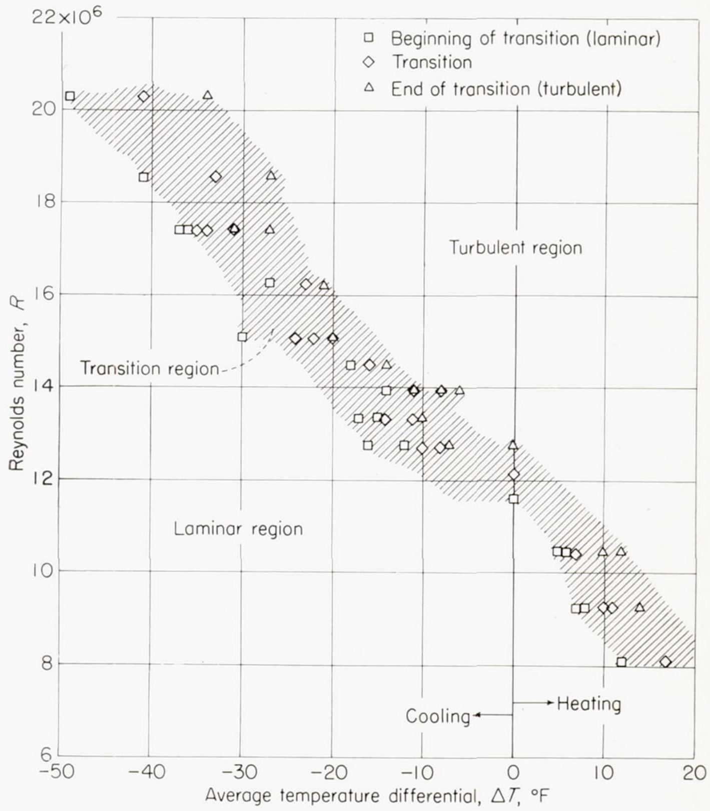


FIGURE 10.—Effect upon boundary-layer transition of heating and cooling NACA RM-10 model with smooth surface. Phase I tests; $M=1.61$; $T_0=109°$ F.

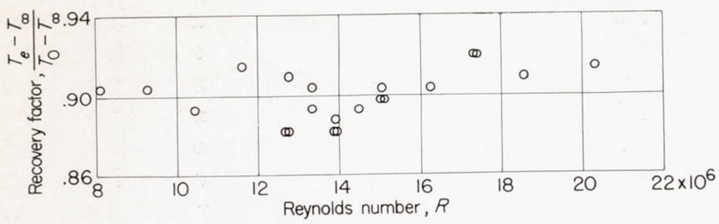


FIGURE 11.—Variation of average model temperature recovery factor with Reynolds number. $M=1.61$; $T_0=109°$ F.

A factor of interest at this point is the fact that, as the average model temperature decreased below about $-50°$ F $\left(\frac{\Delta T}{T_0'}=0.25\right)$, a thin film of hard, translucent ice began to form on the model, with the first appearance and greatest thickness of ice usually occurring at the coldest points on the body $\left(\text{at } \frac{x}{L}=0.30 \text{ to } 0.40\right)$. The longer the model was maintained at these low temperatures, the more ice accumulated. For the extreme cases, the ice covered more than three-fourths of the model surface and, in one instance, covered all of the model except for about a 2- or 3-inch length at the nose. For these cases the boundary-layer flow remained laminar over the entire length of the body. At the higher Reynolds numbers (17.4×10^6 to 20.3×10^6) where ice accumulations were sometimes fairly extensive, an occasional burst of turbulence appeared and almost instantaneously cleared the ice from the model in a triangular region downstream of the point where the turbulence originated. Upon the disappearance of the turbulence ice began to accumulate again in the cleared area. The effects of these turbulence bursts could not be observed on either the boundary-layer pressures or schlieren observations, owing, no doubt, to their short duration.

TRANSITION ON ROUGHENED MODEL

The results of phase I of this investigation on the effects of cooling on boundary-layer transition on the RM–10 with surface roughened were too scanty and of too diverse a nature to be plotted but are presented in table I. In general, when the model surface is roughened, the effectiveness of cooling in increasing the transition Reynolds number was decreased to a maximum incremental value of 1.3×10^6 even for as much as 90° F of cooling. The fact that transition

TABLE I

EFFECTS OF COOLING ON BOUNDARY-LAYER TRANSITION ON NACA RM-10 WITH SURFACE ROUGHENED

Location of roughness strip, x/L	Type of roughness strip	Reynolds number for transition	
		Without heat transfer	With cooling
0.04	No. 60 carborundum grains	7.0×10^6	7.0×10^6
	No. 150 carborundum grains	8.8	9.3
	Shellac only	8.7	9.3
.25	No. 150 carborundum grains	11.5×10^6	12.8×10^6
	Shellac only	11.5	12.8
.50	No. 150 carborundum grains	11.5×10^6	12.8×10^6
	No. 250 carborundum grains	11.5	[a] 17.4
	Shellac only	11.5	12.8

[a] Believed to be affected by large accumulation of ice over roughness strip.

Reynolds number changed only slightly was generally found to hold true regardless of the type of transition strip used, whether one of No. 60 carborundum grains, which fixed transition with no heat transfer at the strip location, or a fine shellac strip, which apparently had no effect at all on transition with no heat transfer.

RESULTS AND DISCUSSION OF PHASE II TESTS

TESTS WITH SMOOTH MODEL

Comparison with previous investigations.—The results from phase II of the investigation of the effects of heating and cooling on boundary-layer transition on the smooth model are presented in figure 12 as a plot of Reynolds number for boundary-layer transition as a function of temperature-difference ratio $\Delta T/T_0'$. Force data and boundary-layer-pressure survey results are differentiated by the use of separate symbols. Included in figure 12 are the results for the beginning of boundary-layer transition obtained in the phase I tests of the NACA RM–10 model (fig. 10) and some typical results (curves A to G) obtained for bodies, wings, and flat plates in other investigations (see refs. 4 to 8). These data, it should be remembered, involve both two- and three-dimensional models and are also affected by differences in Mach number, pressure gradient, surface roughness, wind-tunnel turbulence levels, and other wind-tunnel flow irregularities.

A comparison of the force and boundary-layer-pressure results indicates excellent agreement between the two methods of determining boundary-layer transition. The agreement between the results from phase I and phase II of the investigation on the same model is also very good. The results indicate that, as the model is heated to high temperatures, the rate of change of R_{tr} with $\Delta T/T_0'$ decreases until, at the highest temperatures, the transition Reynolds number and the rate of change of R_{tr} with $\Delta T/T_0'$ are of the same order of magnitude as those found in previous investigations. This result is to be expected, not only because the boundary layer becomes more stable as the Reynolds number is decreased and consequently requires a greater amount of heating for destablization, but also because the curve is asymptotic to the zero Reynolds number axis.

As the model is cooled to lower temperatures, the slope of the curve of R_{tr} plotted against $\Delta T/T_0'$ increases, although the increase is at a slower rate than the decrease in slope encountered with increased model heating. The maximum transition Reynolds number obtained was 28.5×10^6 with a temperature-difference ratio of -0.161, or 92° F of model cooling.

On the basis of the results shown, therefore, the sensitivity of boundary-layer transition to heating or cooling appears to be low when the boundary-layer transition Reynolds number for zero heat transfer is low, and high when this transition Reynolds number is high.

Factors affecting maximum R_{tr} obtainable.—The maximum R_{tr} that could be obtained in these tests was apparently limited by two factors. The first, and probably the more important factor insofar as this investigation is concerned, was the great sensitivity of transition to surface roughness that results at high Reynolds numbers since the boundary

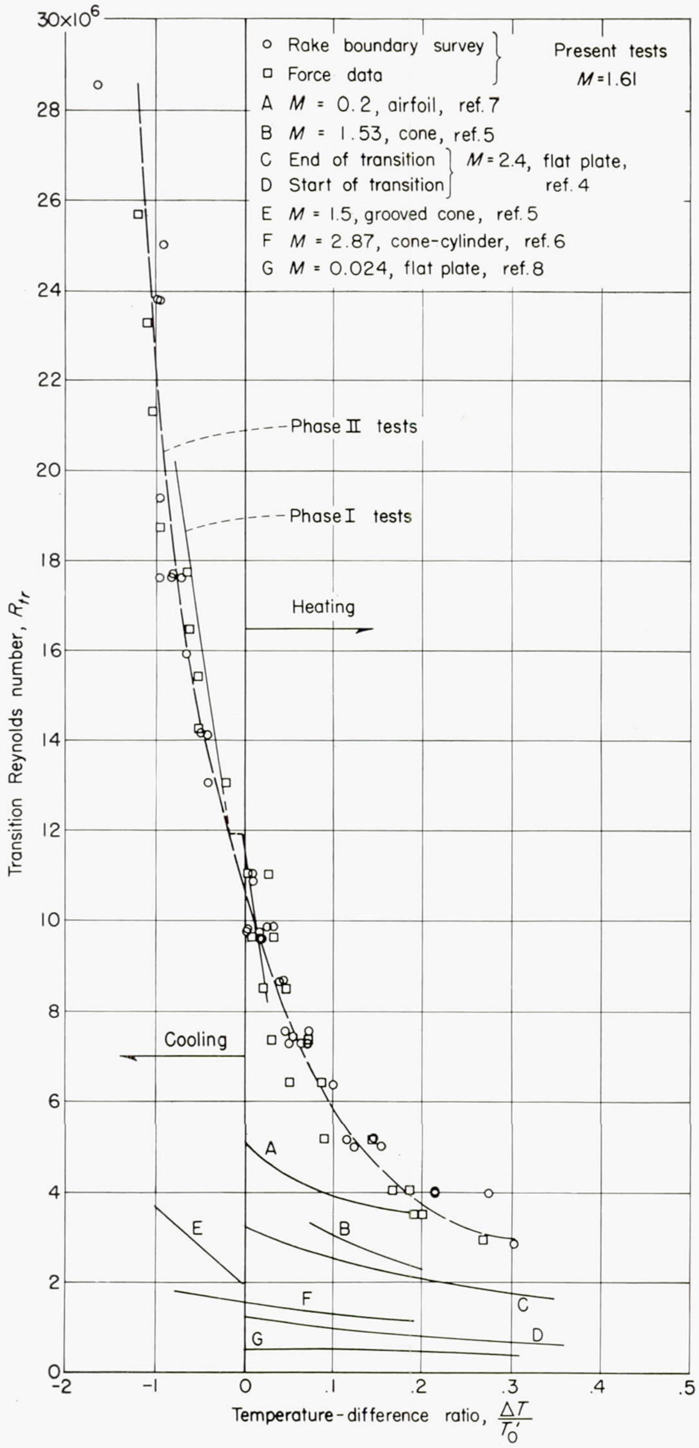


FIGURE 12.—Effect of heating and cooling on boundary-layer transition for present tests and comparison with results from other sources.

layer becomes very thin. For values of R greater than 20×10^6, success in obtaining laminar flow by cooling was a random affair dependent upon the smoothness with which the nose of the model was polished; changes in surface roughness between different runs, so minute as to defy detection, apparently determined whether laminar flow would be obtained. In many other instances during testing (but not in the test runs described above) laminar flow would be obtained for several seconds or more but would disappear before any reliable temperature, force, or pressure data could be obtained. Examination of the model immediately after the run always showed a few minute nicks in the surface attributable to sandblasting. This sandblasting could not be eliminated at the higher tunnel stagnation pressures even with careful cleaning of the tunnel. Also, during tests at high Reynolds numbers, cooling of the model was so slow that a coat of ice with a rough snowlike surface would often form, despite efforts to keep the tunnel unusually dry (dew point of about —45°). This ice probably aided in preventing the attainment of laminar flow. On the basis of these results, therefore, it appears possible that the Tollmien-Schlichting wave type of boundary-layer instability, which is probably predominant at the lower Reynolds numbers, is obscured by effects of surface roughness at higher Reynolds numbers. The sensitivity of laminar boundary-layer stability to surface roughness at high Reynolds numbers with cooling is similar to that experienced at low speeds with boundary-layer suction. This result may be expected because in both cases the boundary layer becomes very thin.

The second factor which influenced the maximum transition Reynolds numbers that could be obtained in this investigation was the lowest temperature that could be obtained near the nose of the model with cooling. This problem is shown in the temperature-distribution plot of figure 9. In some cases the lowest obtainable nose temperature was not as low as the average model temperature. Since at high values of Reynolds number boundary-layer transition occurs near the nose of the model, a deficiency in cooling in this region can easily account for the lack of success in obtaining laminar flow.

Because the average temperature of the model ahead of the point of boundary-layer transition is of considerably greater importance in the study of boundary-layer stability than the average temperature for the whole model which is used in figure 12, the experimental curve is apparently somewhat in error and therefore only qualitative but is consistent with the proper trends. On the basis of the average model temperature ahead of the transition point, the slope of the experimental curve will be considerably increased. The proper average temperature that should be used could not be estimated from these tests.

Comparison with theory.—A comparison of the experimental results obtained in this investigation with the theoretical computations for a flat plate as calculated by Van Driest (ref. 3) is presented in figure 13. The comparison shows that the experimental curve of boundary-layer transition follows the trends of the theoretical curve for initial appearance of boundary-layer instability fairly well except for a displacement toward higher Reynolds numbers. If the experimental results are corrected to equivalent flat-plate Reynolds numbers by division of the Reynolds number by a factor somewhat less than 3 (according to ref. 3, the factor 3 applies to cones), the agreement is better. The results thus may be taken as evidence of the existence of the classical Tollmien-Schlichting wave type of boundary-layer instability in these tests for Reynolds numbers up to the point where surface-roughness effects become predominant. It may be concluded, also, that Lees' theory of boundary-layer stability in compressible flows (ref. 1) as applied by Van Driest (ref. 3)

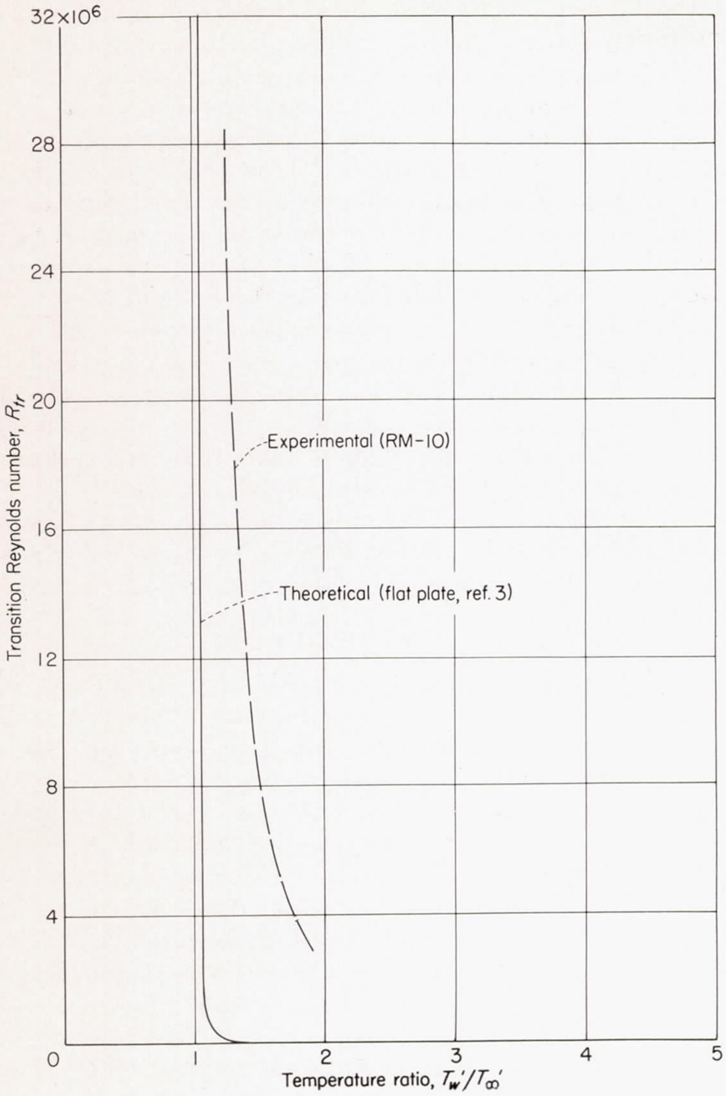


FIGURE 13.—Comparison of experimental transition Reynolds number for NACA RM-10 model and theoretical calculations of boundary-layer stability for flat plate (ref. 3).

can predict fairly well the general trends, at least, of the effect of heat transfer on transition.

The curves of boundary-layer transition (experimental curve) and of boundary-layer instability (theoretical curve) in figure 13 apparently become asymptotic to some critical value or values of the ratio of body-surface temperature to free-stream temperature. Theoretically, the boundary layer will then be stable for all Reynolds numbers (to infinity) for temperature ratios less than this critical value. Since the most powerful effect of cooling on boundary-layer stability or transition occurs in the low range of temperature ratio where the curves approach this asymptotic condition, it is possible that in this range damping would occur for disturbances of appreciable magnitude. Thus, if sufficient cooling were applied to cool the model below the critical temperature for complete stability, then the boundary layer might conceivably lose much of its sensitivity to surface roughness and traverse relatively rough surfaces without undergoing transition. The small amount of additional cooling required in the present case to investigate this possibility can be seen from figure 14, which shows the

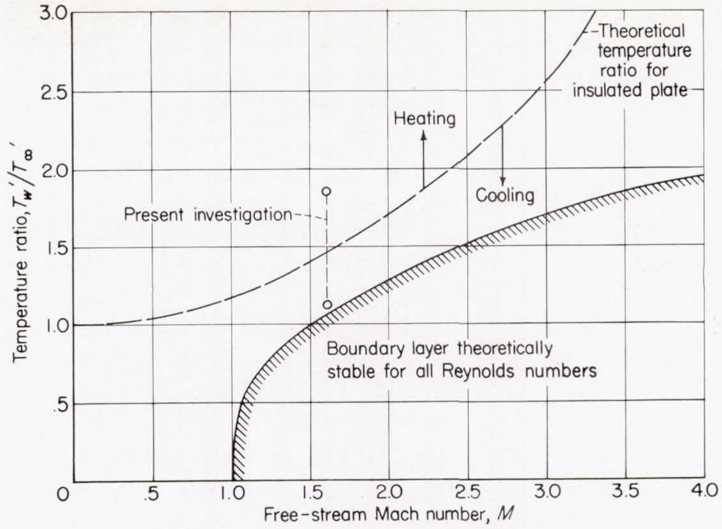


FIGURE 14.—Heating and cooling range covered in boundary-layer-transition investigation on NACA RM-10 model. Theoretical curve from reference 7.

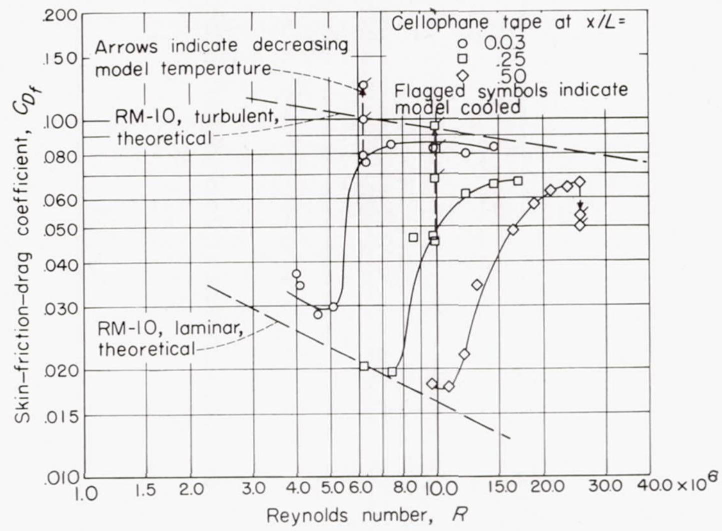


FIGURE 15.—Variation of skin-friction-drag coefficient with Reynolds number for various locations of transition strip, including the effects of cooling. $M=1.61$.

average heating and cooling ranges covered in this investigation and the theoretical ratio of body surface temperature to free-stream temperature required to stabilize completely the boundary layer. A margin to allow for inaccuracy in the theory is desirable.

TESTS WITH SURFACE ROUGHNESS AND TUNNEL FLOW DISTURBANCES

Transition strips.—The results of the force tests made with transition strips of cellophane tape at $x/L=0.03$, 0.25, and 0.50 are presented in figure 15. The theoretical curves were obtained by means of the extended Frankl and Voishel method (ref. 11) for the turbulent boundary layer and the Chapman and Rubesin method (ref. 12) for the laminar boundary layer. Mangler's transformation (ref. 13) was used for the laminar boundary layer and a similar approach was used for the turbulent boundary layer in order to apply the flat-plate calculations to three-dimensional bodies. The short-dashed lines indicate cooling at constant Reynolds

number and the arrows indicate the direction of change in skin-friction drag with decreasing temperature. Too much emphasis should not be placed upon the quantitative values of skin-friction coefficient with cooling, as it is believed that the quantitative accuracy of the balance deteriorates somewhat at low temperatures. The direction of the trends, however, is not affected.

An analysis of the results for the adiabatic or equilibrium conditions (zero heat transfer) shows that the cellophane tape at $x/L=0.03$ and 0.25 caused a reduction in transition Reynolds number, whereas the strip at $x/L=0.50$ had little or no effect. Attempts to obtain completely laminar flow by cooling for the cases with cellophane tape at the two forward locations were unsuccessful, even at Reynolds numbers only slightly above those at which transition first appeared. For the case of cellophane tape at $x/L=0.50$ an attempt was made to obtain completely laminar flow by cooling at $R=25.5 \times 10^6$. It was estimated that, at this Reynolds number, transition was slightly ahead of $x/L=0.50$ for the uncooled or adiabatic condition. The attempt was partly successful in that laminar flow was apparently established up to the strip of cellophane tape although not beyond. These results with surface roughness are apparently analogous to those obtained for the smooth body at high Reynolds numbers in that boundary-layer cooling is not effective in delaying transition when boundary-layer instability is associated predominantly with surface roughness.

Canard surfaces.—In practical airplane and missile configurations wings or small canard surfaces will be placed well forward on the body. In order to investigate the effects of such surfaces on transition with cooling, tests were made with small canard surfaces placed with the leading edge at $x/L=0.16$ (fig. 6) at zero angle of incidence. The results indicated that the surfaces strongly fixed transition at this location for Reynolds numbers as low as 2.5×10^6 and that cooling will be of little avail in obtaining laminar flow behind the surfaces.

Tunnel disturbances.—Past experience has indicated that laminar boundary layers become increasingly susceptible to separation, usually followed by transition, as the Reynolds number is increased. (For example, see ref. 14.) In fact, the indications are that at Reynolds numbers of the order of 20×10^6 to 30×10^6 laminar separation will occur as a result of a static-pressure rise relative to stream dynamic pressure of about 0.5 percent. This pressure rise can be generated by a shock having a turning angle of less than 1/5°. Thus, at these high test Reynolds numbers the laminar boundary layer will separate for pressure rises closely approaching the magnitude of the pressure disturbances that may exist in supersonic wind tunnels. In order to check the validity of this prediction, a series of tests was made with a wooden wedge of 18-inch span mounted on the tunnel floor so that the shock from the leading edge of the wedge would impinge somewhere on the forward half of the model (fig. 6).

The detailed results are not presented but they indicate that even the smallest wedge that could be tested (about 0.7° with a chord of 2 in.) reduced the Reynolds number for transition under adiabatic or zero-heat-transfer conditions. Also, cooling the model was ineffectual in obtaining laminar flow behind the point where the shock from the wedge impinged upon the model. Tests with the wedge replaced by a double thickness of cellophane tape on the tunnel floor showed that the disturbance produced was so small as to have no effect either under conditions with no heat transfer or with cooling as compared with the smooth model without the specially induced disturbances. Apparently, the effects of finite disturbances that could originate in a test section of a supersonic tunnel are very similar to the effects of surface roughness on the ability of heat transfer to influence boundary-layer transition. An analysis, on the basis of reference 14, of the air flow in the region of the test section occupied by the model revealed that considerably higher values of R_{tr} than those obtained in the present investigation should be attainable before the flow disturbances present in the 4- by 4-foot supersonic pressure tunnel would have an effect.

SUMMARY OF RESULTS

An investigation of the effects of heating, cooling, surface irregularities, and airstream disturbances on boundary-layer transition on a parabolic body of revolution has been carried out at Reynolds numbers ranging from 2.5×10^6 to 35×10^6 in the Langley 4- by 4-foot supersonic pressure tunnel. The results obtained are summarized, as follows:

1. Cooling the model increased the Reynolds number for which laminar flow could be maintained over the entire length of the body; heating the model decreased the transition Reynolds number. The trend of the experimental results is in good agreement with that predicted by boundary-layer stability theory.

2. The highest transition Reynolds number obtained in this investigation with cooling was 28.5×10^6. At this Reynolds number the classical Tollmien-Schlichting wave type of boundary-layer instability was apparently obscured by surface-roughness effects.

3. Heating the model an average of 170° F to a ratio of model-surface temperature to free-stream temperature of 1.85 decreased the transition Reynolds number from 11.5×10^6 to about 3×10^6.

4. A comparison of the results obtained for the smooth body with other wind-tunnel results indicated that the effects of heat transfer on transition location are strongly dependent upon the transition Reynolds number for zero heat transfer. If the transition Reynolds number with zero heat transfer is large, as in the present experiments, the sensitivity of transition to heating or cooling is then high. However, if the Reynolds number of transition is low for the adiabatic case, transition is then relatively insensitive to heat-transfer effects.

5. In the presence of airstream disturbances (generated by thin wedges mounted on the test-section floor) and surface irregularities such as circumferential strips of carborundum or of cellophane tape and small canard surfaces,

it was not possible to obtain laminar flow downstream of the irregularity or disturbance by application of the maximum cooling available in the present tests. It should be noted, however, that the lowest wall temperature in these tests was somewhat higher than the theoretical value for infinite stability at a free-stream Mach number of 1.61. It is possible, therefore, that some further reduction in wall temperature might alter this result.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., *February 16, 1953.*

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